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A CONTRIBUTION TO THE THEORY OF IONIZATION WAVES IN THE POSITIV--ETC(U)
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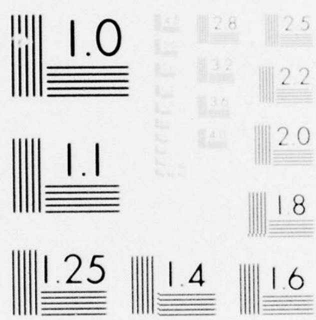
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FOREIGN TECHNOLOGY DIVISION

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By

K. Kolacek

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A CONTRIBUTION TO THE THEORY OF IONIZATION
WAVES IN THE POSITIVE COLUMN OF A
GLOW DISCHARGE

Karel Kolacek

The energy averaging of the Boltzmann-Vlasov kinetic equation is performed for small discharge currents in a one-dimensional approximation on the assumption that the velocity distribution of the electrons is near to the Maxwell distribution.

1. INTRODUCTION

One of the starting equations of the ionizing waves' theory developed at the Physics Institute CSAV in Prague is a linearized energy transfer equation (see /1/)

$$\frac{\partial \vartheta}{\partial z} + a_1 \vartheta = b_1 e, \tag{1}$$

where "z" is the discharge axis (its positive direction here is from the cathode to the anode - for this reason in the equation (1) the signs are changed), ϑ and "e" are electron thermal deviations expressed in energy units and longitudinal electrical field intensities ' deviations from a state of equilibrium. This equation was obtained by linearizing the Granovsky /2/ equation for the energy balance of electron collisions.

In this work the energy transfer equation is exactly deduced from the Boltzmann-Vlasov kinetic equation for electrons

$$\frac{\partial f_e}{\partial t} + c\nabla_r f_e + \frac{F_e}{m_e}\nabla_c f_e = \left[\frac{\delta f_e}{\delta t}\right], \tag{2}$$

for a case of quasi-Maxwellian electron velocities distribution for small discharge currents in a uni-dimensional approximation (not applied to non-homogeneous elements in the radial direction). In the equation (2) f_e is a partition function of the electrons velocities, "t" is time, "c" is instantaneous velocity, ∇_r, ∇_c are operators in the coordinates and velocities' sub-space of the phase space, F_e is the force acting upon the electrons, m_e is the mass of electron, $\left[\delta f_e / \delta t\right]$ is the collision member which expresses ~~in~~ the interaction of electrons among themselves and with all the other particles.

2. DEDUCTION OF THE EQUATION FOR THE TRANSFER ENERGY OF ELECTRONS.

Under laboratory conditions ~~at~~ in low pressure plasma let us assume that the partition function f_e appears in the following manner (as in reference /3/)

(3) $$f_e = K_e \exp\{-\gamma_e m_e[(c_1 - u_e)^2 + c_2^2 + c_3^2]\};$$

$\gamma_e = 1/2kT_e$, "k" is the Boltzmann constant and T_e is the electron temperature, c_i is the i-th element of instantaneous velocity and u_e is the "carrying away" velocity of the electrons (in the direction of the "z" axis). The constant K_e is introduced as a standard for the concentration N_e

$$N_e = \int_{(c)} f_e \, dC.$$

Using the method of reference /3/ it is possible to demonstrate that

(4) $$K_e = N_e \left(\frac{\gamma_e m_e}{\pi}\right)^{3/2}$$

In order to obtain the electrons energy transfer equations, we have to multiply equation (2) by a quadruple of the instantaneous velocity "c" and integrate throughout the velocities' sub-space in the phase space (see also /3/):

(5) $$\int_{(c)} c^2 \frac{\partial f_e}{\partial t} dC + \int_{(c)} c^2 (c\nabla_r) f_e \, dC + \int_{(c)} c^2 \left(\frac{F_e}{m_e} \nabla_c\right) f_e \, dC = \int_{(c)} c^2 \left[\frac{\delta f_e}{\delta t}\right] dC.$$

The first two integrals on the left side of this equation may be calculated simply by expressing the instantaneous velocities in spheric coordinates, carrying out the suitable substitutions, developing in series and by limiting (with a precision of 3 significant figures) ourselves to its first member (see addendum).

The integration method chosen explains the neglect of the kinetic energy of the "carrying away" velocity of the electrons as compared to the thermal energy. If we denote

(6) $$\tfrac{3}{2}kT_e = \Theta,$$

we shall obtain

(7) $$\int_{(c)} c^2 \frac{\partial f_e}{\partial t} \mathrm{d}C = \frac{\partial}{\partial t} \frac{2}{m_e} N_e \Theta,$$

(8) $$\int_{(c)} c^2 (c\nabla_r) f_e \mathrm{d}C = \frac{\partial}{\partial z} \frac{10}{3} \frac{1}{m_e} N_e \Theta u_e.$$

When calculating the third integral we have to make an assumption about the acting forces: in the case of the usual conditions in the positive column glowing discharge F_e is the Lorentz force given by the equation

(9) $$\dot{F}_e = -q_0 E - \frac{q_0}{c_0} [c \times H],$$

where $-q_0$ is the electron charge, "E" and "H" are intensities of the electrical and magnetic fields, C_0 is the velocity of light in vacuum. By a procedure similar to the calculation of the above mentioned integrals we may easily obtain the following (see the addendum):

(10) $$\int_{(c)} c^2 \left(\frac{F_e}{m_e} \nabla_c\right) f_e \mathrm{d}C = -\frac{2}{m_e} q_0 N_e u_e E.$$

The integral on the right side expresses the cooling or heating of electrons by the action of collisions. Later we will provide this equation with an approximation expression and for this purpose we will establish which processes we shall take into account and which we shall neglect. In the meantime let us point out:

(11) $$\int_{(c)} c^2 \left[\frac{\delta f_e}{\delta t}\right] \mathrm{d}C = \frac{2}{m} A.$$

If we substitute the expressions (7), (8), (10) and (11) in (5) and solving for $m_e/2$ we obtain the following equation

(12) $$\frac{\partial}{\partial t}(N_e\Theta) + \frac{5}{3}\frac{\partial}{\partial z}(N_e\Theta u_e) = q_0 N_e u_e E + A .$$

By further arrangements and with the aid of the electrons continuity equation

(13) $$\frac{\partial N_e}{\partial t} + \operatorname{div}(N_e u_e) = \frac{\delta N_e}{\delta t}$$

(where $\frac{\delta N_e}{\delta t}$ expresses the creation and extintion of electrons by ionization and recombination respectively) , we obtain the final energy transfer equation:

(14) $$\frac{\partial\Theta}{\partial t} + u_e\frac{\partial\Theta}{\partial z} = q_0 u_e E - \tfrac{2}{3}u_e\frac{1}{N_e}\frac{\partial N_e\Theta}{\partial z} - \tfrac{2}{3}\Theta\frac{\partial u_e}{\partial z} - \frac{1}{N_e}\Theta\frac{\delta N_e}{\delta t} + \frac{1}{N_e}A .$$

Its' right side we interpret as follows: The first member expresses heating by Joule type heat, the second expresses cooling (or heating) by expansion (or compression), The third expresses cooling (or heating) provided by the space gradient of the electrons "carrying away" velocity, The fourth member expresses cooling caused by heating of cold electrons (just created) to a given temperature (=increase of their kinetic energy to the mean kinetic energy of the remaining electrons), the fifth member expresses cooling or heating ~~xfx~~ of electrons under the influence of collisions and /...illegible.../

a)cooling by elastic collisions with heavy particles, b) cooling by charging (or stepwise charging) of neutral (or charged, or ionized) particles, d)heating by collisions of other kinds.

Let us write further:

(15) $$A = -N_e\sum_k \alpha_k q_0 U_k .$$

where α_k is the frequency of the k-th order of collision for one electron and $q_0 U_k$ is the energy consumed (or gained, then U_k will be negative) during one such collision of the k-th order. Thus we shall obtain the equation (14) in the following form:

$$N_e\left(\frac{\partial\Theta}{\partial t} + u_e\frac{\partial\Theta}{\partial z}\right) = q_0 u_e N_e E - \frac{2}{3}u_e\frac{\partial N_e\Theta}{\partial z} - \frac{2}{3}N_e\Theta\frac{\partial u_e}{\partial z} - \Theta\frac{\delta N_e}{\delta t} - N_e\sum_k \alpha_k q_0 U_k\,. \tag{16}$$

3. LINEARIZATION OF THE ELECTRON ENERGY TRANSFER EQUATION AND DISCUSSION

Let us assume such a plasma disturbance where the magnitudes in the positive column are modified in such a manner that their values become:

$$\begin{aligned} N_e &= N_{e0} + n_e\,, & |n_e| &\ll N_{e0}\,,\\ \Theta &= \Theta_0 + \vartheta\,, & |\vartheta| &\ll \Theta_0\,,\\ E &= E_0 + e\,, & |e| &= |E_0|\,, \end{aligned} \qquad \alpha_k = \alpha_{k0} + \frac{\partial\alpha_k}{\partial\Theta}.\vartheta \tag{17}$$

(the sub-index $_0$ denotes the values in the homogeneous positive column). Equation (16) for the homogeneous column has the following form:

$$q_0 u_e N_{e0} E_0 - N_{e0}\sum_k \alpha_{k0} q_0 U_k = 0\,. \tag{18}$$

Let us substitute the relationships (17) in equation (16), substract equation (18) and after rearranging we obtain:

(19)

$$N_e\frac{\partial\vartheta}{\partial t} + \frac{5}{3}N_e u_e\frac{\partial\vartheta}{\partial z} + N_{e0}\sum_k\frac{\partial\alpha_k}{\partial\Theta}q_0 U_k\vartheta = q_0 u_e N_{e0} e + q_0 u_e E_0 n_e + - \frac{2}{3}u_e\Theta\frac{\partial n_e}{\partial z} - \frac{2}{3}N_e\Theta\frac{\partial u_e}{\partial z} - n_e\sum_k\alpha_{k0}q_0 U_k - \Theta\frac{\delta N_e}{\delta t}\,.$$

From here it is evident that in the analogous equation (1) only the second and third left side members and the first member on the right side of that equation are taken into account, that is, the derivation with respect to time and the members related to the variable count of particles have been neglected.

For further discussion we must express the "carrying away" velocity. We shall use for this purpose the continuity equation (13). Thus it is valid:

$$N_e u_e = -D_e \operatorname{grad} N_e - E\mu_e N_e$$

(where D_e and μ_e are diffusion coefficient and the mobility of electrons, respectively),

also

(20) $$\mu_e = -\frac{D_e}{N_e}\frac{\partial n_e}{\partial z} - \mu_e E.$$

Then from equation (19) it follows that if we consider D_e as a constant and disregard various ~~furthrtx~~ further causes contributing to the "carrying away" velocity u_e which are present in equation (20), we will not get in equation (19) any member expressing the diffusion heat of electrons caused by the temperature gradient (that is, a member containing $\partial^2 \vartheta / \partial z^2$) but solely a member expressing the electrons thermal diffusion caused by the gradient of particles' count (that is, a member containing $\partial^2 n_e / \partial z^2$). The member containing $\partial^2 \vartheta / \partial z^2$ may be obtained only by precising the expression (20) for the "carrying away" velocity. Let us consider if it is possible to make this equation more accurate by these two methods:

1. By expanding u_e by one more member, by the component of the "carrying away" velocity related to the electrons' thermal gradient (of the type $(-1/T_e)$ grad $D_T T_e$). The mechanism of heat diffusion of the electrons is of two types /4/ :

a) transfer of kinetic energy by collisions of the electron-electron type; but because these collisions take place in a low pressure plasma at small currents they are unlikely to occur and may be neglected. b) Penetration of electrons from higher levels of mean kinetic energy into lower mean kinetic energy levels; this manner of diffusion is given only by the concentration gradient which is included just in the "carrying away" velocity.

2. By considering the dependence on temperature of D_e (thermal diffusion - see /5/) where the mobility μ_e can be considered in first approximation as constant (this may easily be generalized), also D_e in the expression $D_e = \mu_e (k T_e)/q_0$ is a linear function of temperature, then

$$u_e = -\frac{1}{N_e}\frac{\partial D_e N_e}{\partial z} - \mu_e E,$$

thus
$$\frac{\partial u_e}{\partial z} = \frac{D_e}{N_e^2}\left(\frac{\partial n_e}{\partial z}\right)^2 - \frac{\partial^2 D_e}{\partial z^2} - \frac{1}{N_e}\frac{\partial D_e}{\partial z}\frac{\partial n_e}{\partial z} - \frac{D_e}{N_e}\frac{\partial^2 n_e}{\partial z^2} - \mu_e \frac{\partial e}{\partial z},$$

and because $D_e = D_e(\Theta(z))$, ...

we have

$$\frac{\partial u_e}{\partial z} = \frac{D_e}{N_e^2}\left(\frac{\partial n_e}{\partial z}\right)^2 - \frac{\partial D_e}{\partial \Theta}\frac{\partial^2 \delta}{\partial z^2} - \frac{1}{N_e}\frac{\partial D_e}{\partial \Theta}\frac{\partial \delta}{\partial z}\frac{\partial n_e}{\partial z} - \frac{D_e}{N_e}\frac{\partial^2 n_e}{\partial z^2} - \mu_e \frac{\partial e}{\partial z}. \tag{21}$$

From this we see that the fourth member on the right side of equation (19), when a linear dependence on temperature is considered for D_e, indicates besides other processes also the electrons' thermal diffusion under the influence of a temperature gradient (second member) and the particles' count gradient (fourth member of expression (21). By other processes we mean here a dependence on the total time variation of the electrons' temperature on the gradient of electric field deviation from the equilibrium state, on the particles' count gradient and on the mixed relationships with the particles' count gradient and the electron temperature gradient.

4. CONCLUSION

For small discharge currents (up to $\approx$10mA/cm^2) we performed in a uni-dimensional approximation an energy averaging of the Boltzmann-Vlasov kinetic equation assuming a quasi-Maxwellian electron velocities distribution. We deducted equations which correspond with equation (1) and have considered a method for a further approximation. In conclusion the author thanks M.Sichov C.Sc., V.Vesely and L.Pekarkov C.Sc. for their valuable suggestions and V.Fuchsov for, besides, a careful proofreading and comments.

ADDENDUM

Calculation of integrals.

1. $\int_{(c)} c^2 \frac{\partial f_e}{\partial t}\, dC$: as a consequence of independence of time, coordinates and instantaneous velocity we may, after solving for f_e^2 (3) and (4) and substituting

(D1) $$c_1 = C\cos\vartheta\,,\quad c_2 = C\sin\vartheta\cos\varphi\,,\quad c_3 = C\sin\vartheta\sin\varphi$$

write $$\int_{(c)} c^2 \frac{\partial f_e}{\partial t}\, dC = \frac{\partial}{\partial t} N_e \left(\frac{\gamma_e m_e}{\pi}\right)^{3/2} \int_{C=0}^{\infty}\int_{\vartheta=0}^{\pi}\int_{\varphi=0}^{2\pi} \cdot$$

where $$\cdot\, C^2 e^{-\gamma_e m_e C^2} e^{h\cos\vartheta} C^2 \sin\vartheta\, dC\, d\vartheta\, d\varphi \,.\, e^{-\gamma_e m_e u_e^2}$$

(D2) $$h = 2\gamma_e m_e u_e C\,.$$

From the relationship $|i| \geqq q_0 N_e |u_e|$ we obtain the magnitude of the "carrying away" velocity of the electrons; for the density of the current $i \gtrsim 10$ mA/cm^2 and concentration $N_e \gtrsim 10^{10}$ cm^{-3} we obtain $u_e \gtrsim 10^6$ cm/s. Further for $T_e \gtrsim 10^4$ °K we arrive at $\gamma_e m_e \gtrsim 10^{-16}$ s^2/cm^2. From here we see that the factor

(D3) $$e^{-\gamma_e m_e u_e^2} \doteq 1 - \frac{\gamma_e m_e u_e^2}{1!} + \ldots \doteq 1\,.$$

By carrying the integration through φ and substituting $\cos\delta = s$ we obtain

$$\int_{(c)} c^2 \frac{\partial f_e}{\partial t}\, dC = \frac{\partial}{\partial t} 2\pi N_e \left(\frac{\gamma_e m_e}{\pi}\right)^{3/2} \int_{C=0}^{\infty} C^4 e^{-\gamma_e m_e C^2} \int_{s=-1}^{1} e^{hs}\, ds\, dC\,.$$

integrating through "s" $\int_{-1}^{1} e^{hs}\,\mathrm{d}s = \frac{2}{h}\sinh h = 2\sum_{l=0}^{\infty}\frac{h^{2l}}{(2l+1)!}$,

and then with (D2) $\int_{(c)} c^2 \frac{\partial f_e}{\partial t}\,\mathrm{d}C = \frac{\partial}{\partial t} 2\pi N_e \left[\frac{\gamma_e m_e}{\pi}\right)^{3/2} \cdot 2\sum_{l=0}^{\infty}\frac{(2\gamma_e m_e)^{2l}}{(2l+1)!} u^{2l}\int_0^{\infty} C^{2l+4}\,\mathrm{e}^{-\gamma_e m_e C^2}\,\mathrm{d}C$,

......

after integration $\int_{(c)} c^2 \frac{\partial f_e}{\partial t}\,\mathrm{d}C = \frac{\partial}{\partial t} N_e \sum_{l=0}^{\infty}\frac{2l+3}{(2l)!!}(2\gamma_e m_e)^{l-1} u^{2l}$.

solving the argument for the l-th member

$$(2\gamma_e m_e)^{l-1} u^{2l} \approx (10^{-15})^{l-1} \cdot (10^6)^{2l} \approx 10^{-3l+15},$$

that is, each following member is by 3 orders smaller than the preceding and it suffices to limit ourselves to l=0. If we introduce (6) we get:

$$\int_{(c)} c^2 \frac{\partial f_e}{\partial t}\,\mathrm{d}C = \frac{\partial}{\partial t}\left(\frac{2}{m_e} N_e \Theta\right).$$

2. $2. \int_{(c)} c^2(c\nabla_r) f_e\,\mathrm{d}C$ 1 is calculated by determining f_e from (3) and (4) and writing out the scalar effects and then substitute in (D1), then (D2) and (D3) obtaining

$$\begin{aligned}\int_{(c)} c^2(c\nabla_r) f_e\,\mathrm{d}C = N_e\left(\frac{\gamma_e m_e}{\pi}\right)^{3/2}\Big\{&\frac{\partial}{\partial z}\int_0^{\infty}\int_0^{\pi}\int_0^{2\pi} C^5\,\mathrm{e}^{-\gamma_e m_e C^2} e^{h\cos\delta}\sin\vartheta\cos\vartheta\,\mathrm{d}C\,\mathrm{d}\vartheta\,\mathrm{d}\varphi\, + \\ &+ \frac{\partial}{\partial x}\int_0^{\infty}\int_0^{\pi}\int_0^{2\pi} C^5\mathrm{e}^{-\gamma_e m_e C^2} e^{h\cos\delta}\sin^2\vartheta\cos\varphi\,\mathrm{d}C\,\mathrm{d}\vartheta\,\mathrm{d}\varphi\, + \\ &+ \frac{\partial}{\partial y}\int_0^{\infty}\int_0^{\pi}\int_0^{2\pi} C^5\mathrm{e}^{-\gamma_e m_e C^2} e^{h\cos\delta}\sin^2\vartheta\sin\varphi\,\mathrm{d}C\,\mathrm{d}\vartheta\,\mathrm{d}\varphi\Big\}.\end{aligned}$$

Both the latter integration members through φ will be eliminated and the first member we solve fully as in the preceding case. Thus we have

$$\int_{(c)} c^2(c\nabla_z) f_e\,\mathrm{d}C = \frac{\partial}{\partial z}\left(\frac{10}{3}\frac{1}{m_e} N_e \Theta u_e\right).$$

.....

3. $\int_{(c)} c^2 \left(\frac{F_e}{m_e} \nabla_c\right) f_e \, dC$ we first simplify the integration by parts (see reference /3/ for details)

$$\int_{(c)} c^2 \left(\frac{F_e}{m_e} \nabla_c\right) f_e \, dC = -\frac{2}{m_e} \int_{(c)} c F_e f_e \, dC ;$$

taking from the relationship (9) and assuming that $\left(\left(c \cdot \frac{q_0}{c_0} [c \times H]\right) = 0,\right.$ we obtain by writing out the scalar effects, again for three members, of which only the first one is of the zero type (by integration through φ). Thus we solve again as in the case 1. and obtain

$$\int_{(c)} c^2 \left(\frac{F_e}{m_e} \nabla_c\right) f_e \, dC = -\frac{2}{m_e} q_0 N_e u_e E .$$

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